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Version of attached file:

Published Version

Peer-review status of attached file:

Peer-reviewed

Citation for published item:

Gonçalves, Dorival and Sakurai, Kazuki and Takeuchi, Michihisa (2017) 'Tagging a monotop signature in natural SUSY.', *Physical review D.*, 95 (1). 015030.

Further information on publisher's website:

<https://doi.org/10.1103/PhysRevD.95.015030>

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Tagging a monotop signature in natural SUSY

Dorival Gonçalves,^{1,2} Kazuki Sakurai,^{1,3} and Michihisa Takeuchi⁴

¹*Institute for Particle Physics Phenomenology, Department of Physics, Durham University, United Kingdom*

²*PITT-PACC, Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*

³*Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, ul. Pasteura 5, 02-093 Warsaw, Poland*

⁴*Kavli IPMU (WPI), UTIAS, University of Tokyo, Kashiwa, 277-8583, Japan*
(Received 2 November 2016; published 30 January 2017)

We study the feasibility of probing a region of natural supersymmetry where the stop and Higgsino masses are compressed. Although this region is most effectively searched for in the monojet channel, this signature is present in many other nonsupersymmetric frameworks. Therefore, another channel that carries orthogonal information is required to confirm the existence of the light stop and Higgsinos. We show that a supersymmetric version of the $t\bar{t}H$ process, $pp \rightarrow t\bar{t}_1\tilde{\chi}_{1(2)}^0$, can have an observably large rate when both the stop and Higgsinos are significantly light, and it leads to a distinctive monotop signature in the compressed mass region. We demonstrate that the hadronic channel of the monotop signature can effectively discriminate the signal from backgrounds by tagging a hadronic top jet. We show that the hadronic channel of the monotop signature offers a significant improvement over the leptonic channel and the sensitivity reaches $m_{\tilde{t}_1} \approx 420$ GeV at the 13 TeV LHC with 3 ab^{-1} luminosity.

DOI: 10.1103/PhysRevD.95.015030

I. INTRODUCTION

The experiment at CERN's LHC has discovered a Higgs-like boson [1,2], yet no sign of new physics beyond the Standard Model has been seen [3]. The gauge hierarchy problem of the Standard Model has become more compelling than ever before. The most promising solution to the gauge hierarchy problem is low-energy supersymmetry (SUSY), where the radiative correction to the Higgs mass-squared parameter from Standard Model particles is cancelled by the contribution from their superpartners, and the electroweak scale is stabilized if sparticles are not significantly heavier than $\mathcal{O}(100)$ GeV. The null result in SUSY searches at the LHC pushes the mass limit for sparticles and creates a tension between the two scales: the naturally expected electroweak scale and the observed one. One way to relax this tension is to arrange the mass spectra such that all SUSY particles are safely beyond the current mass limit but keep the scalar top quark (stop) and the Higgsinos as light as possible. This solution is dubbed as *Natural SUSY* and has been intensively studied [4–45].

The light-stop scenario has also attracted a lot of attention in the experimental community, and many analyses have been dedicated to the light-stop search. One of the most challenging parameter regions is the so-called *compressed region*, where the lighter stop, \tilde{t}_1 , is only slightly heavier than the lightest neutralino, $\tilde{\chi}_1^0$, which is assumed to be the lightest SUSY particle and stable. In this region, the decay products of the stop become very soft and are not reconstructed in the detector. The total missing energy also

becomes very small due to the back-to-back kinematics of the stop pair.

The compressed stop-neutralino region is intensively searched for by looking at the monojet signature [46,47] in which the stop pair system is boosted recoiling against hard QCD initial-state radiation, creating a large missing energy. Although this search channel is very powerful in terms of discovery, there is an important drawback. Its final state is characterized by large missing energy associated with high p_T jet(s), and none of the high p_T objects comes directly from stops. Indeed, as illustrated in the left panel of Fig. 1, the produced particles ξ and ξ' are not necessarily stops but may be anything as long as they convert into the missing particle χ , producing only soft particles that cannot be reconstructed in the detector. The same final state can also be realized by a single production of X accompanied by hard QCD radiation followed by an invisible decay $X \rightarrow \chi\chi$ or a resonant production of X followed by $X \rightarrow q(g) + \chi$. The list goes on. Finding a monojet signature thus by no means indicates the existence of a light stop nor the solution to the hierarchy problem [48–50].

In Ref. [51], we have pointed out that, in addition to the monojet channel, the light stop and Higgsinos, if present in nature, must generate another phenomenologically attractive channel, namely, $pp \rightarrow t\bar{t}_1\tilde{\chi}_i^0$ ($i = 1, 2$).¹ The relation between $pp \rightarrow \tilde{t}_1\tilde{t}_1^*$ and $pp \rightarrow t\bar{t}_1\tilde{\chi}_i^0$ is analogous to

¹We do not explicitly distinguish the particle and the anti-particle in writing $pp \rightarrow t\bar{t}_1\tilde{\chi}_i^0$. The baryon and flavor numbers are, however, always conserved in this process.

DELPHES3. Only the cells with the transverse energy larger than 0.5 GeV are taken into account. We take advantage of the hadronic top in the boosted regime by reclustering the calorimeter towers into a fat jet with the radius parameter of $R = 1.5$ using the Cambridge/Aachen jet algorithm implemented in FASTJET [85]. We require at least one fat jet with $p_{TJ} > 200$ GeV, $|\eta_J| < 2.5$, and this jet must be top tagged by the HEPToPTAGGER [72,73]. The HEPToPTAGGER was initially designed to reconstruct mildly boosted top quarks with $p_{T,t} \sim m_t$. However, large flexibility of the algorithm allows achieving a good tagging efficiency $\sim 30\%$ for highly boosted tops, $p_{T,t} \gtrsim 400$ GeV, keeping the fake rate within the level of 3%. The red solid histogram in Fig. 3 shows the top-tagging efficiency as a function of the top quark $p_{T,t}$. Also shown in Fig. 3 by the blue dotted histogram is the mistag rate for QCD jets as a function of the fat jet $p_{T,J}$. The tagging efficiency is estimated in the signal sample, while the mistag rate is obtained in the $Z + \text{jets}$ sample.

To further suppress the $Z + \text{jets}$ background, we also require at least one of the three subjets—inside the fat jet—to be b tagged, assuming the b -tagging efficiency of 70% and the mistag rate of 1%. After a successful top tagging, we remove the tagged top-jet constituents and recluster the remaining calorimeter towers, but now with the anti- k_T jet algorithm with $R = 0.4$, $p_{Tj} > 30$ GeV and $|\eta_j| < 2.5$. To suppress the dominant $t\bar{t}$ background, we apply an extra-jet veto, $n_j = 0$. We have checked that relaxing this condition (e.g., $n_j \leq 1$) only deteriorates the sensitivity due to the overwhelming contribution from the $t\bar{t}$ background, even when rejecting extra b -tagged jets.

It is interesting to compare the hadronic and leptonic monotop channels. In Fig. 4, we show the E_T distributions for the hadronic (red) and leptonic (blue) channels of the

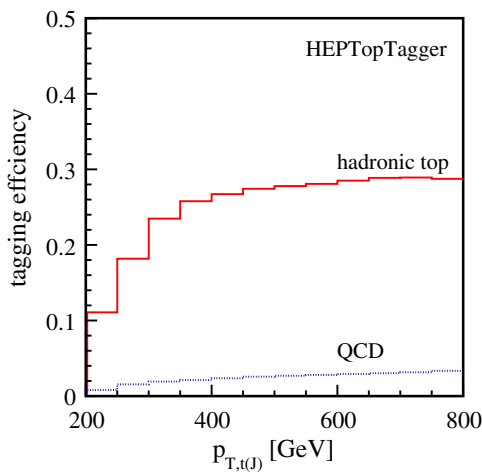


FIG. 3. Top tagging efficiency as a function of the top quark $p_{T,t}$ derived from the HEPToPTAGGER algorithm. The dotted line shows the mistag rate as a function of the fat jet $p_{T,J}$ originated from QCD jets in the $Z + \text{jets}$ sample.

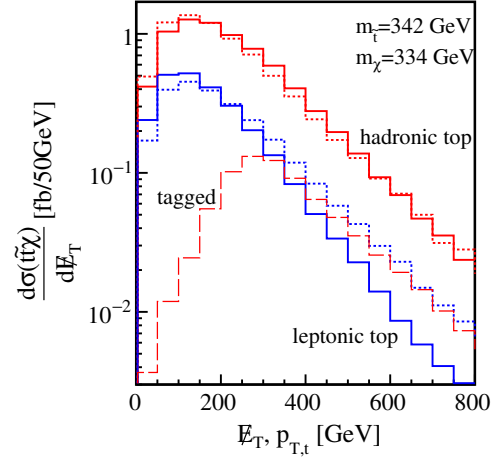


FIG. 4. E_T distribution for leptonic (blue) and hadronic (red) top decays for $t\tilde{t}_1\tilde{\chi}_{1(2)}^0$ in the benchmark point of $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}) = (342 \text{ GeV}, 334 \text{ GeV})$. The dotted lines are the respective top $p_{T,t}$ distributions, and the dashed line shows only the tagged contribution.

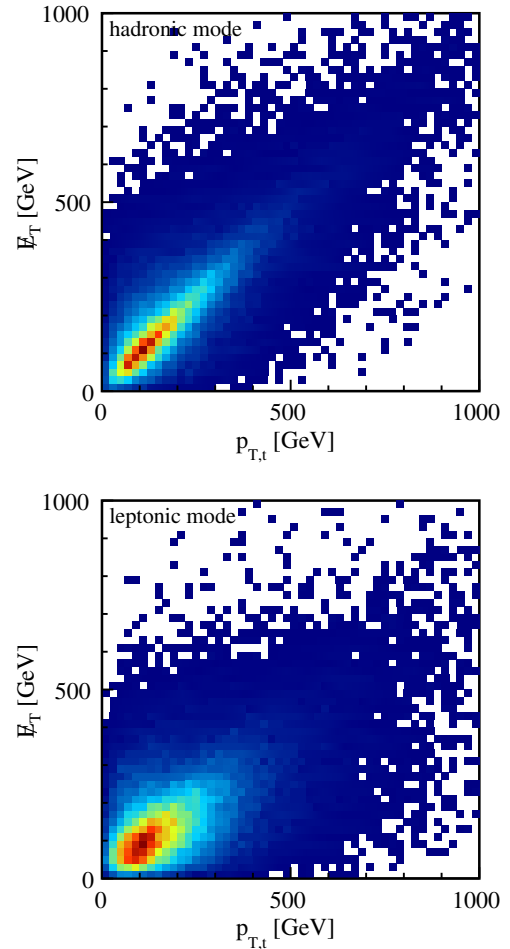


FIG. 5. 2D $(p_{T,t}, E_T)$ distribution for the hadronic (top) and leptonic (bottom) channels. The dense regions are shown in red. Notice that the leptonic final state provides a softer E_T profile as the neutrino momentum from the top-quark decay partly cancels the missing transverse energy generated by neutralinos.

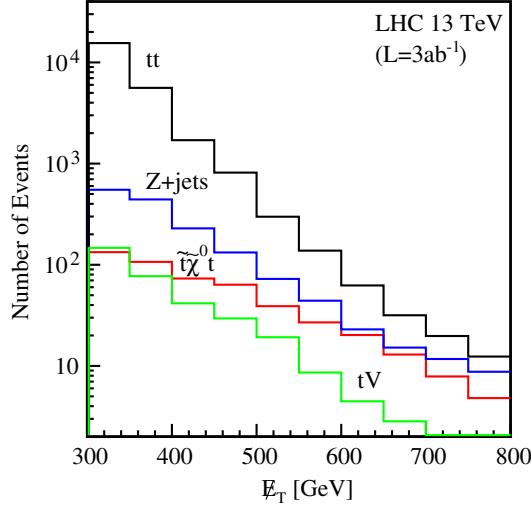


FIG. 6. Signal and backgrounds transverse missing energy \cancel{E}_T distributions at the 13 TeV LHC. We consider the signal benchmark point $m_{\tilde{t}_1} = 342$ GeV, $m_{\tilde{\chi}_1^0} = 334$ GeV.

$pp \rightarrow t\tilde{t}_1\tilde{\chi}_{1(2)}^0$ process in the solid lines. The corresponding dotted histograms are the truth level top-quark $p_{T,t}$ distributions. The hadronic final state has a much larger rate due to the greater hadronic branching ratio, $\mathcal{BR}_{\text{had}} \sim 0.68$, of the top quark. We can also see that the hadronic channel leads to more energetic \cancel{E}_T distribution in comparison with the leptonic one, which is shown in the corresponding solid lines. The source of this larger \cancel{E}_T can be appreciated by looking at the 2D $(p_{T,t}, \cancel{E}_T)$ distributions shown in the top (for the hadronic channel) and bottom (for the leptonic channel) plots in Fig. 5. While the hadronic top fully balances the transverse momentum with the two neutralinos in the final state ($\vec{p}_T = -\vec{p}_{t,T}$), in the leptonic channel, the \cancel{E}_T generated by the neutralinos is partly cancelled by the neutrino from the top-quark decay. It is also worth noting that this cancellation in \cancel{E}_T in the leptonic channel is more significant for larger \cancel{E}_T bins, where the hadronic top

tagging becomes most efficient due to the boosted kinematics of the top quark as explicitly seen in the tagged top $p_{T,t}$ distribution (red dashed). As a result, the number of events with $\cancel{E}_T \gtrsim 400$ GeV in the hadronic channel exceeds that in the leptonic channel even after taking the top-tagging efficiency into account.

In Fig. 6, we display the \cancel{E}_T distribution for the signal and background samples after the full event selections. We observe that the signal-to-background ratio, S/B , increases in the region with large \cancel{E}_T . To exploit this feature, we divide our analysis into three signal regions, \mathcal{SR} , that differ by the \cancel{E}_T requirement as $\cancel{E}_T > 400, 500$, and 600 GeV. The full cut-flow analysis is provided in Table I.

III. RESULTS

We now show the performance of our hadronic mono-top analysis assuming the 13 TeV LHC with $\mathcal{L} = 3 \text{ ab}^{-1}$ and compare it with the leptonic analysis studied in Ref. [51]. In the left ($\tilde{t}_1 = \tilde{t}_L$) and the right ($\tilde{t}_1 = \tilde{t}_R$) panels of Fig. 7, the 95% C.L. sensitivity regions derived from the hadronic monotop analysis are highlighted by the light red color. When deriving the sensitivity, we choose the most sensitive signal region with the largest S/\sqrt{B} . To ensure that the systematic uncertainty is under control, we only consider the regions with $S/B > 0.1$. The three benchmark points in Table I are denoted by the stars. As can be seen, the performance of this analysis is not sensitive to whether the \tilde{t}_1 is dominantly \tilde{t}_L or \tilde{t}_R . In comparison, we also show the 95% C.L. sensitivity derived from the leptonic monotop analysis [51] with the black dashed curve. It is clear that the sensitivity from the hadronic analysis is superior in all regions. For example, in the most compressed ($m_{\tilde{t}_1} \simeq m_{\tilde{\chi}_1^0}$) region, the sensitivity reaches $m_{\tilde{t}_1} \sim 420$ GeV for the hadronic channel, while the sensitivity for the leptonic channel is limited up to $m_{\tilde{t}_1} \sim 380$ GeV for both \tilde{t}_L and \tilde{t}_R cases. As we have discussed in detail in the previous section, the

TABLE I. Cut-flow analysis for the signal and backgrounds at the LHC $\sqrt{s} = 13$ TeV. The numbers of signal and background events are shown assuming $\mathcal{L} = 3 \text{ ab}^{-1}$.

| Model point | $t\tilde{t}_1\tilde{\chi}_{1(2)}^0$ | | | $\tilde{t}t$ | tW | tZ | $Z + \text{jets}$ | Total background |
|--|-------------------------------------|------------|------------|--------------|------|------|-------------------|------------------|
| | (342 334) | (394 368) | (394 386) | | | | | |
| $n_\ell = 0$, top-tag, $p_{TJ} > 200$ GeV, $\cancel{E}_T > 300$ GeV | 2103 | 1275.8 | 1245.5 | 128924 | 8821 | 1260 | 68923 | 207928 |
| b tag in t_{tag} (70%, 1% \times 3 combinatorial) | 1472 | 893.0 | 871.8 | 90246 | 6174 | 882 | 2068 | 99370 |
| $n_j = 0$ ($p_{Tj} > 30$ GeV, $ \eta_j < 2.5$) | 507.1 | 240.9 | 288.4 | 24248 | 2520 | 168 | 1550 | 28486 |
| $\mathcal{SR}1$: $\cancel{E}_T > 400$ GeV | 267.0 | 124.4 | 160.8 | 3114 | 504 | 52.5 | 556.5 | 4227 |
| $\mathcal{SR}2$: $\cancel{E}_T > 500$ GeV | 130.4 | 57.8 | 83.5 | 595.6 | 105 | 25.2 | 195.2 | 921.0 |
| $\mathcal{SR}3$: $\cancel{E}_T > 600$ GeV | 64.5 | 26.5 | 44.7 | 151.5 | 29.4 | 10.5 | 74.7 | 266.1 |
| S/B and S/\sqrt{B} for $\mathcal{SR}1$ | (0.06,4.1) | (0.03,1.9) | (0.04,2.5) | | | | | |
| for $\mathcal{SR}2$ | (0.14,4.3) | (0.06,1.9) | (0.09,2.8) | | | | | |
| for $\mathcal{SR}3$ | (0.24,4.0) | (0.1,1.6) | (0.17,2.7) | | | | | |

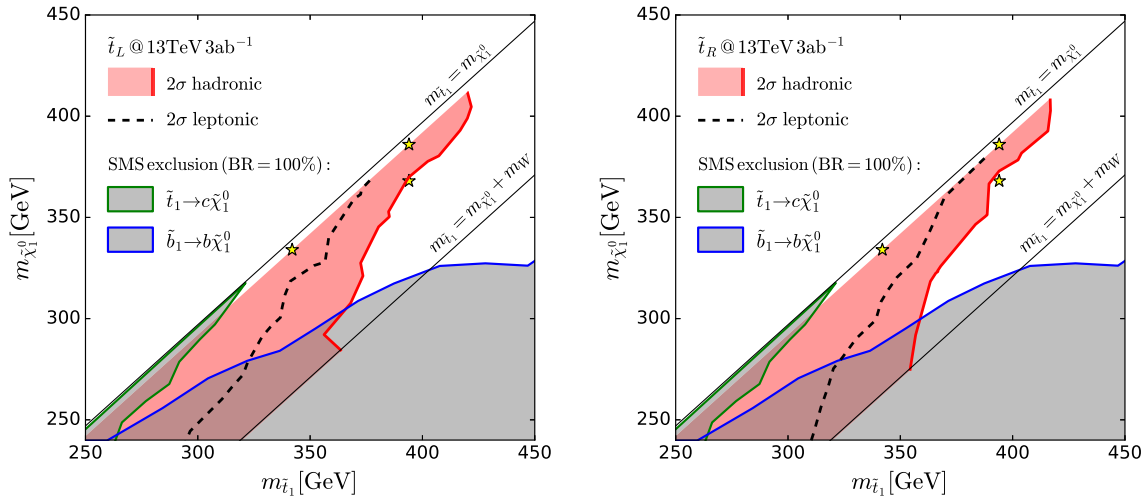


FIG. 7. Expected 95% C.L. sensitivities at the 13 TeV high-luminosity LHC $\mathcal{L} = 3 \text{ ab}^{-1}$. The light red regions in the left and right panels correspond to the 2σ regions for the $\tilde{t}_1 = \tilde{t}_L$ and $\tilde{t}_1 = \tilde{t}_R$ cases, respectively, obtained by the hadronic monotop analysis presented in this paper. The black dashed contours are the 2σ regions obtained by the leptonic monotop analysis shown in Ref. [51]. The current 95% C.L. excluded regions based on simplified models for SUSY assuming 100% branching ratio are also shown in gray. The blue and green curves are obtained from the di- b jet [87] and monojet [46] analyses based on the 13 TeV data with $\mathcal{L} = 3.2 \text{ fb}^{-1}$.

superiority of the hadronic channel is attributed to $\mathcal{BR}_{\text{had}} \gg \mathcal{BR}_{\text{lep}}$ and the absence of the partial cancellation in the \vec{E}_T between the neutralinos and the neutrino in the leptonic channel. We also superimpose the current exclusion limits² derived in simplified models assuming 100% branching ratios of the \tilde{t}_1 . The gray region surrounded by the green curve is excluded by the 13 TeV ATLAS monojet analysis [46] assuming $\mathcal{BR}(\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0) = 100\%$, whereas the gray region with the blue curve is excluded by the 13 TeV ATLAS di- b jet analysis [87] assuming $\mathcal{BR}(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0) = 100\%$. Strictly speaking, the latter limit cannot be directly applied to the $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ plane. However, in our setup with the \tilde{t}_1 predominantly decaying into b and Higgsino-like $\tilde{\chi}_1^\pm$ with $m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_1^0}$, both production rates and event topologies are similar between $pp \rightarrow \tilde{t}_1 \tilde{t}_1 \rightarrow b\tilde{\chi}_1^+ b\tilde{\chi}_1^-$ and $pp \rightarrow \tilde{b}_1 \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0 b\tilde{\chi}_1^0$. So, this limit can be applied at least approximately. We also comment that these published exclusion limits are sensitive to the \tilde{t}_1 decay. On the other hand, the monotop analysis presented in this paper is less sensitive to it since the high- p_T objects used in the analysis did not originate from the \tilde{t}_1 decay but from the top-quark decay.

²The preliminary result of CMS [86] claims their excluded region reaches $m_{\tilde{t}_1} \sim 380 \text{ GeV}$ in the most mass-degenerate region assuming $\mathcal{BR}(\tilde{t}_1 \rightarrow b\tilde{f}'\tilde{\chi}_1^0) = 100\%$. This strong exclusion is achieved by explicitly looking at soft b jets from $\tilde{t}_1 \rightarrow b\tilde{f}'\tilde{\chi}_1^0$. This technology would also improve the sensitivity of our monotop analysis to the $pp \rightarrow \tilde{t}_1 \tilde{t}_{1(2)}^0$ process. However, we leave this analysis for future work.

IV. CONCLUSION

We have studied a class of natural SUSY models in which the stop and Higgsinos have almost equal masses. It has been known that this compressed region can be most effectively searched for by the monojet channel, exploiting hard QCD initial-state radiation. The drawback of the monojet channel is that the high p_T jet is entirely controlled by QCD and does not carry information on the stop and Higgsino sectors. Indeed, finding this signature does not necessarily indicate the existence of the light stop and Higgsino. To probe the stop and Higgsino sectors, another channel providing orthogonal information is required.

In this paper, we have studied a supersymmetric version of the $\tilde{t}\tilde{t}H$ process, namely, $\tilde{t}\tilde{t}\tilde{\chi}_{1(2)}^0$ production. In the region where the mass spectrum is compressed ($m_{\tilde{t}_1} \simeq m_{\tilde{\chi}_1^0}$), this process leads to a distinctive monotop signature. The three-particle production process $pp \rightarrow \tilde{t}\tilde{t}\tilde{\chi}_{1(2)}^0$ can have observably large rates only if both the stop and Higgsinos are significantly light. The monotop signature can thus be regarded as the smoking gun signature of the compressed region of the natural SUSY scenario.

We focused in this article on the hadronic final state of the monotop signature with an obvious advantage of $\mathcal{BR}_{\text{had}} \gg \mathcal{BR}_{\text{lep}}$. To discriminate the signal from backgrounds, we have used HEPToPTAGGER to tag a boosted hadronic top in the signal. We found a superior performance in the sensitivity for the hadronic monotop analysis over the previously studied leptonic analysis [51]. This is attributed not only to $\mathcal{BR}_{\text{had}} \gg \mathcal{BR}_{\text{lep}}$ but also to the fact that \vec{E}_T is harder in the hadronic channel than in the

leptonic one because the E_T generated by the neutralinos is partially cancelled by the neutrino from the top-quark decay in the leptonic channel. After performing Monte Carlo simulation including the detector effects, we have found the sensitivity in the hadronic monotop analysis reaches $m_{\tilde{t}_1} \approx 420$ GeV, exhibiting a significant improvement over the leptonic analysis of which the reach is $m_{\tilde{t}_1} \approx 380$ GeV. We also observed that, in order to suppress the background, very large E_T (e.g., $E_T > 400\text{--}600$ GeV) is required. The E_T is highly correlated to the top quark p_T , and the top tagging becomes most efficient in the high- p_T region. We therefore expect that the hadronic monotop channel works well also for the light-stop and Higgsino searches at future 100 TeV pp colliders.

ACKNOWLEDGMENTS

D. G. and K. S. were supported by STFC through the IPPP grant. The work of D. G. was also partly funded by the U.S. National Science Foundation under Grant No. PHY-1519175. The work of K. S. is partially supported by the National Science Centre, Poland, under research Grants No. DEC-2014/15/B/ST2/02157 and No. DEC-2015/18/M/ST2/00054. M. T. is supported by World Premier International Research Center Initiative (WPI Initiative), MEXT, Japan. M. T. is supported by Grant-in-Aid for Scientific Research, Grants No. JP16H03991 and No. JP16H02176. D. G. and M. T. are grateful to the Mainz Institute for Theoretical Physics for its hospitality and its partial support in the early stages of this work.

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